Hidden Gauge Symmetries: A New Possibility at the Colliders

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We consider a new physics possibility at the colliders: the observation of TeV scale massive vector bosons in the non-adjoint representations under the Standard Model (SM) gauge symmetry. To have a unitary and renormalizable theory, we propose a class of models with gauge symmetry $\prod_i G_i \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y$ where the SM fermions and Higgs fields are singlets under the hidden gauge symmetry $\prod_i G_i$, and such massive vector bosons appear after the gauge symmetry is spontaneously broken down to the SM gauge symmetry. We discuss the model with $SU(5)$ hidden gauge symmetry in detail, and comment on the generic phenomenological implications.

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Introduction – The Standard Model (SM), based on the local gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$, is very successful in describing all the experimental results below the TeV scale as an excellent effective field theory, although it is widely believed that it is not the whole story. Discovery of new particles is highly anticipated at the colliders, especially the Large Hadron Collider (LHC). The most likely and reasonably well motivated candidates are the Higgs bosons, superpartners of ordinary particles, and the extra Z' boson. However, it is important to think of other alternatives or entirely new possibilities before the LHC turns on.

In the SM, we have fermions (spin 1/2) and scalars (Higgs fields) (spin 0) which do not belong to adjoint representations under the SM gauge symmetry. Can we also have TeV scale vector bosons (spin 1) which belong to the non-adjoint representations under the SM gauge symmetry? Can we construct a renomalizable theory realizing such a possibility? These are very interseting theoretical questions that we will address in this work. Discovery of these massive vector bosons at the LHC will open up a new window for our understanding of the fundamental theory describing the nature.

How can we construct a consistent theory involving the massive vector bosons which do not belong to the adjoint representations under the SM gauge symmetry? If the massive vector bosons are not the gauge bosons of a symmetry group, there are some theoretical problems from the consistency of quantum field theory, for instance, the unitarity and renormalizability [1]. On the other hand, the gauge bosons are massless if the gauge symmetry is exact. When the gauge symmetry is spontaneously broken via the Higgs mechanism, the interactions of the massive gauge bosons satisfy both the unitarity and the renormalizability of the theory [2, 3]. Thus, the massive vector bosons must be the gauge bosons arising from the spontaneously gauge symmetry breaking.

As we know, a lot of models with extra TeV scale gauge bosons have been proposed previously in the literature. However, those massive gauge bosons either belong to the adjoint representations or are singlets under the SM gauge symmetry [4, 5, 6, 7, 8, 9, 10]. For example, in the top color model [4, 5, 6], the colorons belong to the adjoint representation of the $SU(3)_C$; in the top flavor model [7, 8], the extra W and Z bosons belong to the adjoint representation of the $SU(2)_L$, while in the $U(1)'$ model [9], the new Z' boson is a singlet under the SM gauge symmetry. In the Grand Unified Theories such as $SU(5)$ and $SO(10)$ [11, 12], there are such kind of massive gauge bosons, however, their masses are around the unification scale $\sim 10^{16}$ GeV to satisfy the proton decay constraints. Thus, we have to propose a new class of models.

When we embed the SM gauge groups into larger groups (not necessarily a semi-simple group), in general, we may have the massive gauge bosons that do not belong to the adjoint representation under the SM gauge symmetry. However, there are stringent constraints on the TeV scale massive gauge bosons from various experiments, for instance, the Tevatron and the LEP. To be consistent with all the current data, we consider a gauge symmetry $\mathcal{G} \equiv \prod_i G_i \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y$. The quantum numbers of the SM fermions and Higgs fields under the $SU(3)'_C \times SU(2)'_L \times U(1)'_Y$ gauge symmetry are the same as those of them under the SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$, while they are all singlets under $\prod_i G_i$. Hence $\prod_i G_i$ is the hidden gauge symmetry. After the gauge symmetry $\mathcal{G}$ is spontaneously broken down to the SM gauge symmetry at the TeV scale via Higgs mechanism, some of the massive gauge bosons from the $\mathcal{G}$ breaking do not belong to the adjoint representations under the SM gauge symmetry. These TeV scale gauge bosons may be observable at the LHC, Tevatron Run 2, and future International Linear Collider (ILC), and may give us an indication of a new hidden gauge symmetry of the nature beyond the SM gauge symmetry. Interestingly, in the string model buildings, there generically exists the additional gauge symmetry which can be considered as our hidden gauge symmetry [13].

For simplicity, we consider one hidden gauge group, *i.e.*, $\mathcal{G} \equiv G \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y$, because the discussions for the general models are quite similar. There are many choices for G, for example, $G = SU(2)$, $SU(3)$, $SU(4)$, G_2, F_4, $Sp(4)$, $Sp(6)$, $SU(5)$, $SO(10)$, E_6, etc. After the gauge symmetry $\mathcal{G}$ is spontaneously broken down to the SM gauge symmetry, the possible non-adjoint representations of the massive gauge bosons under the SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$ in these models are

$$\begin{aligned}
&(\mathbf{1}, \mathbf{1}, \mathbf{Q_1}) \oplus (\mathbf{1}, \mathbf{1}, -\mathbf{Q_1}) \ , \ (\mathbf{1}, \mathbf{2}, \mathbf{Q_2}) \oplus (\mathbf{1}, \mathbf{2}, -\mathbf{Q_2}) \ , \\
&(\mathbf{3}, \mathbf{1}, \mathbf{Q_3}) \oplus (\bar{\mathbf{3}}, \mathbf{1}, -\mathbf{Q_3}) \ , \ (\mathbf{3}, \mathbf{1}, \mathbf{0}) \oplus (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{0}) \ , \\
&(\mathbf{6}, \mathbf{2}, \mathbf{Q_4}) \oplus (\bar{\mathbf{6}}, \mathbf{2}, -\mathbf{Q_4}) \ , \ (\mathbf{6}, \mathbf{1}, \mathbf{Q_5}) \oplus (\bar{\mathbf{6}}, \mathbf{1}, -\mathbf{Q_5}) \ , \\
&(\bar{\mathbf{3}}, \mathbf{3}, \mathbf{Q_6}) \oplus (\mathbf{3}, \mathbf{3}, -\mathbf{Q_6}) \ , \ (\mathbf{3}, \mathbf{2}, \mathbf{Q_7}) \oplus (\bar{\mathbf{3}}, \mathbf{2}, -\mathbf{Q_7}) \ , \\
&(\mathbf{1}, \mathbf{3}, \mathbf{Q_8}) \oplus (\mathbf{1}, \mathbf{3}, -\mathbf{Q_8}) \ , \qquad (1)
\end{aligned}$$

where $Q_i \neq 0$. In our models, there generically exist the massive gauge bosons which belong to the adjoint representations under the SM gauge symmetry. Because we are not interested in the adjoint massive gauge bosons that have been studied previously [4, 5, 6, 7, 8], we emphasize that we do not consider them in this paper.

To be concrete, we shall give the formalism realizing our idea for a simple model with $G = SU(5)$.

Formalism – We consider a model with $\mathcal{G} \equiv SU(5) \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y$ gauge symmetry where $SU(5)$ is a hidden gauge symmetry. We denote the gauge fields for $SU(5)$ and $SU(3)'_C \times SU(2)'_L \times U(1)'_Y$ as $\widehat{A}_\mu$ and $\widetilde{A}_\mu$, respectively, and the gauge couplings for $SU(5)$, $SU(3)'_C$, $SU(2)'_L$ and $U(1)'_Y$ are g_5, g'_3, g'_2 and g'_Y, respectively. The Lie algebra indices for the generators of $SU(3)$, $SU(2)$ and $U(1)$ are denoted by $a3$, $a2$ and $a1$, respectively, and the Lie algebra indices for the generators of $SU(5)/(SU(3) \times SU(2) \times U(1))$ are denoted by $\hat{a}$. After the $SU(5) \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y$ gauge symmetry is broken down to the SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$, we denote the massless gauge fields for the SM gauge symmetry as A^{ai}_μ, and the massive gauge fields as B^{ai}_μ and $\widehat{A}^{\hat{a}}_\mu$. The gauge couplings for the SM gauge symmetry $SU(3)_C$, $SU(2)_L$ and $U(1)_Y$ are g_3, g_2 and g_Y, respectively.

To break the $SU(5) \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y$ gauge symmetry down to the SM gauge symmetry, we introduce four bifundamental Higgs fields U_1, U_2, U_3 and U_4 with the following quantum numbers:

Fields	$SU(5)$	$SU(3)'_C \times SU(2)'_L \times U(1)'_Y$
U_1	$\mathbf{5}$	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1/3})$
U_2	$\bar{\mathbf{5}}$	$(\mathbf{3}, \mathbf{1}, -\mathbf{1/3})$
U_3	$\mathbf{5}$	$(\mathbf{1}, \mathbf{2}, -\mathbf{1/2})$
U_4	$\bar{\mathbf{5}}$	$(\mathbf{1}, \mathbf{2}, \mathbf{1/2})$

In order to break the $SU(5) \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y$ gauge symmetry down to the SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$, we only need two Higgs fields, one from the U_1 and U_2, and the other one from the U_3 and U_4. The reason, for choosing four Higgs fields U_1, U_2, U_3 and U_4, is that we can generalize this non-supersymmetric model to the supersymmetric model without adding the new particle contents except the superpartners of the particles.

To give the vacuum expectation values (VEVs) to the bifundamental Higgs fields U_i, we consider the following potential

$$\begin{aligned}
V \ = \ & \sum_{i=1}^{4} \left[\lambda_i \left(|U_i|^2 - \tilde{v}_i^2 \right)^2 + \tilde{m}_i^2 |U_i|^2 \right] + \lambda_{12} |U_1 U_2 - \tilde{v}_{12}^2|^2 \\
& + \lambda_{34} |U_3 U_4 - \tilde{v}_{34}^2|^2 + \left[\tilde{m}_{12}^2 U_1 U_2 + \tilde{m}_{34}^2 U_3 U_4 \right. \\
& + \lambda_{1234} U_1 U_2 U_3 U_4 + \frac{y_{13}}{M_{13}} U_1 U_1 U_1 U_3 U_3 \\
& \left. + \frac{y_{24}}{M_{24}} U_2 U_2 U_2 U_4 U_4 + \text{H.C.} \right] \ , \qquad (2)
\end{aligned}$$

where M_{13} and M_{24} need not be at the GUT scale or Planck scale, and can be the mass scales of the heavy fields because the non-renormalizable operators can be obtained from the renormalizable operators by integrating out the heavy fields. In addition, there is no global symmetry in above potential except the gauge symmetry $SU(5) \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y$, so, there is no Goldstone boson.

We choose the following VEVs for the fields U_i

$$< U_1 >= v_1 \begin{pmatrix} I_{3\times3} \\ 0_{2\times3} \end{pmatrix} \ , \quad < U_1 >= v_2 \begin{pmatrix} I_{3\times3} \\ 0_{2\times3} \end{pmatrix} \ , \ (3)$$

$$< U_3 >= v_3 \begin{pmatrix} 0_{3\times2} \\ I_{2\times2} \end{pmatrix} \ , \quad < U_4 >= v_4 \begin{pmatrix} 0_{3\times2} \\ I_{2\times2} \end{pmatrix} \ , \ (4)$$

where $I_{i\times i}$ is the $i \times i$ identity matrix, and $0_{i\times j}$ is the $i \times j$ matrix where all the entries are zero. We asuume that v_i $(i = 1, 2, 3, 4)$ are in the TeV range so that the massive gauge bosons have TeV scale masses.

From the kinetic terms for the fields U_i , we obtain the mass terms for the gauge fields

$$\begin{aligned}
& \sum_{i=1}^{4} \langle (D_\mu U_i)^\dagger D^\mu U_i \rangle = \frac{1}{2} \left(v_1^2 + v_2^2 \right) \left(g_5 \widehat{A}^{a3}_\mu - g'_3 \widetilde{A}^{a3}_\mu \right)^2 \\
& + \frac{1}{2} \left(v_3^2 + v_4^2 \right) \left(g_5 \widehat{A}^{a2}_\mu - g'_2 \widetilde{A}^{a2}_\mu \right)^2 \\
& + \left(\frac{v_1^2}{3} + \frac{v_2^2}{3} + \frac{v_3^2}{2} + \frac{v_4^2}{2} \right) \left(g_5^Y \widehat{A}^{a1}_\mu - g'_Y \widetilde{A}^{a1}_\mu \right)^2 \\
& + \frac{1}{2} g_5^2 \left(v_1^2 + v_2^2 + v_3^2 + v_4^2 \right) \left(X_\mu \overline{X}_\mu + Y_\mu \overline{Y}_\mu \right) \ , \qquad (5)
\end{aligned}$$

where $g_5^Y \equiv \sqrt{3} g_5 / \sqrt{5}$, and we define the complex fields $(X_\mu,\ Y_\mu)$ and $(\overline{X}_\mu,\ \overline{Y}_\mu)$ with quantum numbers $(\mathbf{3},\ \mathbf{2},$

$-\mathbf{5/6}$) and ($\bar{\mathbf{3}}$, $\mathbf{2}$, $\mathbf{5/6}$), respectively from the gauge fields $\widehat{A}_\mu^{\hat{a}}$, similar to that in the usual $SU(5)$ model [11].

From the original gauge fields $\widehat{A}_\mu^{ai}$ and $\widetilde{A}_\mu^{ai}$ and from Eq. (5), we obtain the massless gauge bosons A_μ^{ai} and the TeV scale massive gauge bosons B_μ^{ai} ($i = 3, 2, 1$) which are in the adjoint represenations of the SM gauge symmetry

$$\begin{pmatrix} A_\mu^{ai} \\ B_\mu^{ai} \end{pmatrix} = \begin{pmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{pmatrix} \begin{pmatrix} \widehat{A}_\mu^{ai} \\ \widetilde{A}_\mu^{ai} \end{pmatrix} , \tag{6}$$

where $i = 3, 2, 1$, and

$$\sin\theta_j \equiv \frac{g_5}{\sqrt{g_5^2 + (g_j')^2}} \ , \ \sin\theta_1 \equiv \frac{g_5^Y}{\sqrt{(g_5^Y)^2 + (g_Y')^2}} \ , \tag{7}$$

where $j = 3, 2$. We also have the massive gauge bosons (X_μ, Y_μ) and ($\overline{X}_\mu$, $\overline{Y}_\mu$) which are not in the adjoint representations of the SM gauge symmetry. So, the $SU(5) \times SU(3)_C' \times SU(2)_L' \times U(1)_Y'$ gauge symmetry is broken down to the diagonal SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$, and the theory is unitary and renormalizable. The SM gauge couplings g_j ($j = 3, 2$) and g_Y are given by

$$\frac{1}{g_j^2} \ = \ \frac{1}{g_5^2} + \frac{1}{(g_j')^2} \ , \ \frac{1}{g_Y^2} \ = \ \frac{1}{(g_5^Y)^2} + \frac{1}{(g_Y')^2} \ . \tag{8}$$

If the theory is perturbative, the upper and low bounds on the gauge couplings g_5, g_3', g_2' and g_Y' are

$$g_3 \ < \ g_5 \ < \ \sqrt{4\pi} \ , \ g_3 \ < \ g_3' \ < \ \sqrt{4\pi} \ , \tag{9}$$

$$g_2 \ < \ g_2' \ < \ \frac{g_3 g_2}{\sqrt{g_3^2 - g_2^2}} \ , \tag{10}$$

$$g_Y \ < \ g_Y' \ < \ \frac{\sqrt{3} g_3 g_Y}{\sqrt{3g_3^2 - 5g_Y^2}} \ . \tag{11}$$

Note that the gauge coupling g_5 for $SU(5)$ is naturally large at the TeV scale because the beta function of $SU(5)$ is negative, *i.e.*, $SU(5)$ is asymptotically free.

Phenomenological Implications – The interactions among the gauge bosons of $SU(5) \times SU(3)_C' \times SU(2)_L' \times U(1)_Y'$ can be obtained from the kinetic terms of the gauge fields. For instance, the interactions between the SM gauge bosons A_μ^{aj} and the massive gauge bosons B_μ^{aj} are given by

$$\begin{aligned} -\mathcal{L}_{\rm gauge} \ = \ & \frac{1}{2} g_j \left[A^3 + 3AB^2 + 2\cot 2\theta B^3\right] \\ & + \frac{1}{4} g_j^2 \left[A^4 + 6A^2B^2 + 4\left(2\cot 2\theta\right) AB^3 \right. \\ & \left. + \left(\tan^2\theta + \cot^2\theta - 1\right) B^4\right] \ , \end{aligned} \tag{12}$$

where $j = 2, 3$. The A^3 and A^4 represent schematically the usual three and four point gauge interactions, respectively

$$A^3 \equiv f_{abc} \left(\partial_\mu A_{\nu a} - \partial_\nu A_{\mu a}\right) A_b^\mu A_c^\nu \ , \tag{13}$$

$$A^4 \equiv f_{abc} f_{ade} A_{\mu b} A_{\nu c} A_d^\mu A_e^\nu \ . \tag{14}$$

And we choose the similar convention for the other terms. Note that a single heavy boson B_μ^{a3} does not couple to two or three gluons, and hence can only be pair produced via the gluon-gluon fusions, or s-chanel gluon exchanges, or t-chanel B_μ^{a3} exchanges at the hadronic colliders such as the LHC.

Similarly, the gauge bosons X^μ and Y^μ will couple to the SM gauge bosons via the gauge kinetic terms for the $SU(5)$ gauge bosons. So, they can be pair produced from the fusions of the SM gauge bosons, or s-chanel SM gauge boson exchanges, or t-chanel X^μ and Y^μ exchanges in the colliders, for instance, the gluon fusions for the hadronic colliders.

The interactions between the gauge bosons and the SM fermions can be obtained from the kinetic terms of the SM fermions. For example, let us consider the quark doublet Q_i with quantum number ($\mathbf{1}$, $\mathbf{3}$, $\mathbf{2}$, $\mathbf{1/6}$) under the gauge symmetry $SU(5) \times SU(3)_C' \times SU(2)_L' \times U(1)_Y'$. The Lagrangian for Q_i is

$$-\mathcal{L} \ = \ \overline{Q_i} \gamma^\mu D_\mu Q_i \ , \tag{15}$$

where

$$\begin{aligned} D_\mu \ \equiv \ & \partial_\mu - i g_3' T^{a3} \widetilde{A}_\mu^{a3} - i g_2' T^{a2} \widetilde{A}_\mu^{a2} - i \frac{1}{6} g_Y' \widetilde{A}_\mu^{a1} \\ = \ & \partial_\mu - i g_3 T^{a3} \left(A_\mu^{a3} + \cot\theta_3 B_\mu^{a3}\right) \\ & - i g_2 T^{a2} \left(A_\mu^{a2} + \cot\theta_2 B_\mu^{a2}\right) \\ & - i \frac{1}{6} g_Y \left(A_\mu^{a1} + \cot\theta_1 B_\mu^{a1}\right) \ . \end{aligned} \tag{16}$$

We emphasize that although the gauge symmetry $SU(5) \times SU(3)_C' \times SU(2)_L' \times U(1)_Y'$ is broken down to the SM gauge symmetry at TeV scale, there is no proton decay problem in our model. The reason is that the gauge bosons (X_μ, Y_μ) and ($\overline{X}_\mu$, $\overline{Y}_\mu$) can not couple to the SM fermions directly, hence they will not produce the observable proton decay. Moreover, note that the bifundamental Higgs fields U_i are in the fundamental representation of $SU(5)$ while the SM fermions are $SU(5)$ singlets, hence any operator, which involves the SM fermions and the U_i fields, has at least two fermions and two U_i fields. Thus, any such operator has dimension 5 or higher, and then will be suppressed by the cut-off scale in the theory, which, for example, is the Planck scale. Thus, the bifundamental Higgs fields U_i will not generate the proton decay problem.

The model proposed here has two kinds of the new vector bosons with masses at TeV scale: one kind of gauge bosons belongs to the adjoint representations of the SM gauge symmetry, while the other kind of gauge bosons (X_μ, Y_μ) and ($\overline{X}_\mu$, $\overline{Y}_\mu$) has quantum numbers ($\mathbf{3}$, $\mathbf{2}$, $-\mathbf{5/6}$) and ($\bar{\mathbf{3}}$, $\mathbf{2}$, $\mathbf{5/6}$) under the SM gauge symmetry. Both kinds of massive gauge bosons have many phenomenological implications which can be tested at the upcoming LHC. In the following, we list some of these phenomenological implications:

(i) The massive QCD type gauge bosons B_μ^{a3} belonging to the $(\mathbf{8}, \mathbf{1}, \mathbf{0})$ representation of the SM gauge symmetry will couple to the gluons, and will be dominantly pair produced via the gluon-gluon fusions, or s-chanel gluon exchanges, or t-chanel B_μ^{a3} exchanges at the LHC. They will decay dominantly to $q\bar{q}$ pairs. Thus, the 4 jet high p_T signal will be significantly enhanced compaired to that in the SM due to these heavy gluon productions.

(ii) The heavy electroweak type gauge bosons, with quantum numbers $(\mathbf{1}, \mathbf{3}, \mathbf{0})$ and $(\mathbf{1}, \mathbf{1}, \mathbf{0})$ under the SM gauge symmetry, will be singly produced at the LHC via $q\bar{q}$ annihilations, as well as will be pair produced via the WW and ZZ fusions. The decays of the heavy photon and Z boson to the lepton pair l^+l^- will give very clean signals.

(iii) The signals of these gauge bosons B_μ^{ai} $(i = 3, 2, 1)$ are very different from those in the topcolor and topflavor models, as our gauge bosons couple to all three families of the SM fermions universally.

(iv) These TeV scale gauge bosons will produce the off-shell effects in the future ILC, and will also contribute to $g_\mu - 2$.

(v) The gauge bosons in the non-adjoint representations of the SM gauge symmetry (such as X_μ and Y_μ type particles in this simple model) can also be pair produced via the gluon fusions, or s-chanel gluon exchanges, or t-chanel massive gauge bosons (for example, X_μ and Y_μ) exchanges at the LHC. Because their couplings to the SM fermions are highly suppressed and they can not decay to the bifundamental Higgs fields U_i due to the kinematics reason, they will be meta-stable and behave like the stable heavy quarks and anti-quarks. If produced at the LHC, they can be detected by their ionizations as they pass through the detector.

(vi) Choosing the different groups for the hidden gauge symmetry G, such as $SU(2)$, $SU(3)$ and $SU(4)$, etc, we can have the massive gauge bosons with different non-adjoint representations under the SM gauge symmetry. Note that in some of these models, the massive gauge bosons and the bifundamental Higgs fields do not cause the proton decay, and thus the massive gauge bosons' couplings to the SM fermions via the bifundamental Higgs fields by the non-renormalizable operators need not to be Planck scale suppressed. So, their productions and subsequent decays might give rise to the other interesting signals at the LHC.

Although we have discussed the phenomenological implications, mostly for the LHC, our proposal has similar implications for the ongoing Tevatron Run 2, and off-shell effects in the future ILC. If our proposed massive vector bosons are light enough, the color octet (B_μ^{a3}) can be pair produced or the electroweak massive bosons $(B_\mu^{a1,2})$ can be singly produced at the Tevatron Run 2, giving rise to similar signals as at the LHC. Also the metastable X_μ and Y_μ bosons can be pair produced, and can be searched by looking for their ionization tracks. We encourage the Run 2 Groups to look for these signals.

Conclusions – We have proposed the interesting new physics possibility at the colliders: the observation of TeV scale massive vector bosons belonging to the non-adjoint representations under the SM gauge symmetry. A class of the $\prod_i G_i \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y$ models realizing this possibility is presented, where such vector bosons are generated when the $\prod_i G_i \times SU(3)'_C \times SU(2)'_L \times U(1)'_Y$ gauge symmetry is spontaneously broken down to the SM gauge symmetry via the Higgs mechanism. These theories are thus unitary as well as renormalizable. The observation of such gauge bosons at the Tevatron Run 2, the LHC, or the future ILC will open up a new window for our understanding of physics beyond the Standard Model.

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